

INTERFACIAL REACTION BETWEEN SAC305 AND SAC405 LEAD-FREE
SOLDERS AND ELECTROLESS NICKEL/IMMERSION SILVER (ENImAg)
SURFACE FINISH

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Dedicated to my beloved father and mother who taught me to trust in Allah, love, encouragement and prays of day and night make me able to get such success.



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ABSTRACT

The different surface finish and solder size on printed circuit board strongly affect the formation of intermetallic compounds (IMCs) and solder joint reliability. Among of various surface finish in the electronic industry, electroless nickel/immersion gold is the most popular at the moment. However, because their black pad issues, electroless nickel/immersion silver (ENImAg) was developed as an alternative surface finish. Therefore, the effect on an interfacial reaction between lead-free solder and ENImAg surface finish using different solder ball size ($\varnothing 300\mu\text{m}$, $\varnothing 500\mu\text{m}$ and $\varnothing 700\mu\text{m}$) was investigated. All samples were subjected to an aging process with different aging times. The characterizations of IMC formation were examined by image analyzer, scanning electron microscopy and energy dispersive x-ray. The results showed that ENImAg finish was free from the black pad nickel. Subsequently, the solder ball size has a significant effect on the IMC formation and fracture surface of as-reflowed and aged solder joint. The IMC thickness of larger solder balls was found to be thicker ($1.74\ \mu\text{m}$) than smaller solder balls ($1.32\ \mu\text{m}$) during soldering. In contrast to aged solder joints, the smaller solder ball produced thicker ($3.51\ \mu\text{m}$) IMC compared to bigger solder balls ($2.47\ \mu\text{m}$). Furthermore, the fracture surface of smaller solder ball size showed ductile mode for both reflowed and aged solder joints. In addition, the solder joint on ENImAg surface finish displayed a thinner layer and smaller grain sizes compared to solder joint on bare copper.

ABSTRAK

Kemasan permukaan dan saiz bebola yang berbeza ke atas papan litar bercetak memberi kesan terhadap pembentukan sebatian antara logam (IMC) dan kebolehpercayaan penyambungan pateri. Antara pelbagai kemasan permukaan dalam industri elektronik, nikel tanpa elektrik/rendaman emas adalah yang paling popular pada masa ini. Bagaimanapun, disebabkan oleh isu pad hitam, nikel tanpa elektrik/rendaman perak (ENImAg) dihasilkan sebagai alternatif kemasan permukaan. Oleh itu, kesan terhadap tindak balas antara muka di antara pateri bebas plumbum dan kemasan permukaan ENImAg bersama-sama dengan saiz bebola pateri yang berbeza iaitu $\text{Ø}300\mu\text{m}$, $\text{Ø}500\mu\text{m}$ and $\text{Ø}700\mu\text{m}$ telah dijalankan. Semua sampel melalui proses penuaan dengan masa penuaan yang berbeza. Ciri-ciri pembentukan IMC telah dianalisis dengan menggunakan penganalisis imej, mikroskop imbasan electron (SEM) dan tenaga serakan x-ray. Hasil keputusan menunjukkan bahawa, kemasan ENImAg didapati bebas daripada pad hitam nikel. Seterusnya, saiz bebola pateri mempunyai kesan yang ketara terhadap pembentukan IMC dan kekuatan ricih selepas proses pengaliran semula dan penuaan. Bola pateri yang bersaiz besar mempunyai ketebalan ($1.74\ \mu\text{m}$) IMC yang lebih tebal berbanding bebola pateri bersaiz kecil ($1.32\ \mu\text{m}$) ketika proses pengaliran semula. Berbeza daripada bebola pateri yang terdedah pada suhu penuaan, bebola pateri yang lebih kecil menghasilkan ketebalan ($3.51\ \mu\text{m}$) IMC yang lebih tebal berbanding bebola pateri yg bersaiz besar ($2.47\ \mu\text{m}$). Tambahan pula, selepas proses pengaliran semula dan penuaan, permukaan patah untuk bebola pateri yan bersaiz kecil menunjukkan mod mulur. Tambahan lagi, penyambungan pateri ke atas kemasan permukaan ENImAg menghasilkan IMC yang nipis, dan saiz bijian yang kecil berbanding penyambungan pateri ke atas tembaga.

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LIST OF SYMBOLS AND ABBREVIATIONS

Ag	-	Silver
Au	-	Gold
Cu	-	Copper
In	-	Indium
Ni	-	Nickel
P	-	Phosphorous
Pb	-	Lead
Pd	-	Palladium
Sb	-	Antimony
Sn	-	Tin
Zn	-	Zinc
BGA	-	Ball Grid Array
CPU	-	Central Processing Unit
DCA	-	Direct Chip Attach
DIP	-	Dual in Line Package
ECA	-	Electrical Circuit Assembly
EDX	-	Energy Dispersive X-Ray
ENEPIG	-	Electroless Nickel/Electroless Palladium/Immersion Gold
ENIG	-	Electroless Nickel/Immersion Gold
ENImAg	-	Electroless Nickel/Immersion Silver
FC	-	Flip Chip
FESEM	-	Field Emission Scanning Electron Microscope

HASL	- Hot-Air Solder Levelling
I/O	- Input/Output
IC	- Integrated Circuit
ImAg	- Immersion Silver
IMC	- Intermetallic Compound
ImSn	- Immersion Tin
JEDEC	- Joint Electron Device Engineering Council
JEIDA	- Japan Electronic Industries Development Association
MCM	- Multi Chip Module
NEMI	- National Electronic Manufacturing Initiative
OM	- Optical Microscope
OSP	- Organic Solderability Preservative (OSP)
PBB	- Poly-Brominated Biphenyls
PBDE	- Poly-Brominated Diphenyl Ethers
PCB	- Printed Circuit Board
PTH	- Plated Through Hole
PWB	- Printed Wire Bond
RoHS	- Restriction of Hazardous Substance
SAC	- Tin-Silver-Copper
SEM	- Scanning Electron Microscope
SMD	- Surface Mount Device
SMT	- Surface Mount Technology
TAB	- Tape Automated Bonding
TCM	- Thermal Conduction Module
WEEE	- Waste from Electrical and Electronic Equipment
XRD	- X-ray Diffraction

REFERENCES

- Agarwala, R. C., & Agarwala, V. (2003). Electroless alloy/composite coatings : A review. *Sadhana*, 28(3-4), 475–493.
- Aisha, S. R., Ourdjini, A., Wah, N.M., How, H.C., & Chin, Y. T. (2010). Interfacial Reactions of SAC305 and SAC405 Solders on Electroless Ni(P)/ Immersion Au and Electroless Ni(B)/Immersion Au Finishes. *Proc. of the 34th Int. Conf. on Electronic Manufacturing Technology*. Melaka, Malaysia: IEEE. pp. 2–7.
- Akhtar, A. M. Z., Wirda, K. H., Rabiattull, I. S., & Mahadzir, I. (2014). Microstructure Evolution at the Solder Joint during Isothermal Aging. In *Proc. of the 36th Int. Conf. on Electronic Manufacturing Technology*. Johor, Malaysia: IEEE. pp. 1–5.
- Aleksinas, M. J. (1990). Chapter 3 Troubleshooting Electroless Nickel Plating Solutions. Mallory, G.O & Hajdu, J.B. *Electroless Plating - Fundamentals and Applications*. United State of America: William Adrew. pp. 101–109.
- Anderson, I. E., Cook, B. a, Harringa, J., Terpstra, R. L., Foley, J. C., & Unal, O. (2002). Effects of Alloying in Near-Eutectic Tin – Silver – Copper Solder Joints. *Material Transaction*, 43(8), 1827–1832.
- Arra, M., Shangguan, D., Xie, D., Sundelin, J., Lepistö, T., & Ristolainen, E. (2004). Study of Immersion Silver and Tin Printed-Circuit-Board Surface Finishes in Lead-Free Solder Applications. *Journal of Electronic Materials*, 33(9), 977–990.
- Aziz, M. S. A., Abdullah, M. Z., Khor, C. Y., & Ani, F. C. (2013). Influence of pin offset in PCB through-hole during wave soldering process : CFD modeling approach. *International Communications in Heat and Mass Transfer*, 48, 116–123.
- Azlina, O. S., Ourdjini, A., & Aisha, I. S. R. (2012). Effect of Nickel Doping on Interfacial Reaction between Lead-Free Solder and Ni-P Substrate. *Advanced Materials Research*, 488–489, 1375–1379.
- Azmah Hanim, M. A., Ourdjini, A., Saliza Azlina, O., & Aisha, S. R. (2013). Intermetallic Evolution for Isothermal Aging Up To 2000 Hours On Sn-4Ag-

- 0.5Cu and Sn-37Pb Solders With Ni/U Layers. *International Journal of Automotive and Mechanical Engineering (IJAME)*, 8(0), 1348–1356.
- Azmah Hanim, M. A., Ourdjini, A., Siti Rabiatal Aisha, I., & Saliza Azlina, O. (2013). Effect of Isothermal Aging 2000 Hours on Intermetallics Formed between Ni-Pd-Au with Sn-4Ag-0.5Cu Solders. *Advanced Materials Research*, 650, 194–199.
- Baheti, V. A., Islam, S., Kumar, P., Ravi, R., Hongqun, D., Vuorinen, V., Laurila, T. & Paul, A. (2015). Effect of Ni content on the diffusion-controlled growth of the product phases in the Cu(Ni) – Sn system. *Philisophical magazine*, 96(1), 15-30.
- Baldwin, D.F. (2005). *Chip Scale, Flip Chip, and Advanced Chip Packaging Technologies. Electronic Packaging and Interconnection Handbook*, Fourth Edition. New York: McGraw-Hill.
- Bang, W. H., Kim, C. U., Kang, S. H., & Oh, K. H. (2009). Fracture mechanics of solder bumps during ball shear testing: Effect of bump size. *Journal of Electronic Materials*, 38(1), 1896–1905.
- Barbetta, M. (2004). The search for the universal surface finish. *Printed Circuit Design and Manufacture*, 21(2), 34–43.
- Baskaran, I., Narayanan, T. S. N. S., & Stephen, A. (2006). Effect of accelerators and stabilizers on the formation and characteristics of electroless Ni–P deposits. *Materials Chemistry and Physics*, 99(1), 117–126.
- Bernasko, P. K., Mallik, S., & Takyi, G. (2015). Effect of intermetallic compound layer thickness on the shear strength of 1206 chip resistor solder joint. *Soldering & Surface Mount Technology*, 27(1), 52–58.
- Bin, Y., & Yabing, Z. (2012). Key Failure Modes of Solder Joints on ENIG PCBs and Root Cause Analysis. *Proc. of the 13th Int. Conf. on Electronic Packaging Technology & High Density Packaging (ICEPT-HDP)*. Guangxi, China: IEEE. pp. 1205–1208.
- Callister, W.D. (2003). *Materials Science and Engineering an Introduction*. 6th Edition. New York: John Wiley & Sons.

- Cannon, M., Klenke, B., & Zarrow, P. (2006). Improving Hand Soldering Operational Costs and Process Control. *Circuits Assembly*, 17(7), 1–4.
- Chaillot, A., Venet, N., Hokka, J., Defense, A., Space, T. A., & Defense, A. (2013). Enepig Finish : An Alternative Solution for Space Printed Circuit. *Proc. of the Conf. Microelectronics Packaging (EMPC)*. Eurpoean: IEEE. pp. 1–6.
- Chan, Y. C., So, A. C. K., & Lai, J. K. L. (1998). Growth kinetic studies of Cu–Sn intermetallic compound and its effect on shear strength of LCCC SMT solder joints. *Materials Science and Engineering: B*, 55(1–2), 5–13.
- Chan, Y. C., & Yang, D. (2010). Failure mechanisms of solder interconnects under current stressing in advanced electronic packages. *Progress in Materials Science*, 55(5), 428–475.
- Chang, K. C., & Chiang, K. N. (2004). Aging study on interfacial microstructure and solder-ball shear strength of a wafer-level chip-size package with Au/Ni metallization on a Cu pad. *Journal of Electronic Materials*, 33(11), 1373–1380.
- Chen, C., Tong, H. M., & Tu, K. N. (2010). Electromigration and Thermomigration in Pb-Free Flip-Chip Solder Joints. *Annual Review of Materials Research*, 40(1), 531–555.
- Chen, Y. H., Wang, Y. Y., & Wan, C. C. (2007). Microstructural characteristics of immersion tin coatings on copper circuitries in circuit boards. *Surface and Coatings Technology*, 202(3), 417–424.
- Cheng, R., Jiang, K., & Li, X. (2011). Enhanced solder joint bonding strength of electronic packaging with electrowetting effect. *Microelectronic Engineering*, 88(11), 3244–3248.
- Choi, W. K., Kang, S. K., & Shih, D. Y. (2002). A study of the effects of solder volume on the interfacial reactions in solder joints using the differential scanning calorimetry technique. *Journal of Electronic Materials*, 31(11), 1283–1291.
- Chung, C. K., & Tai, S. F. (2004). Evolution of Ag₃Sn During Reflow Soldering. *Thermal and Thermomechanical Phenomena in Electronic Systems*, 2(0), 116–120.

- Cioci, R., Pecht, M., & Ganesan, S. (2006). *Lead-Free Electronics: Overview. Lead Free Electronic*. New Jersey: John Wiley & Sons, Inc.
- Cullen, D. P., & O'Brien, G. (2004). Implementation of immersion silver PCB surface finish in compliance with Underwriters Laboratories. *Proc. of the IPC Printed Circuits Expo*. SEMA Council APEX. pp. 1–10.
- Dele-Afolabi, T. T., Azmah Hanim, M. a., Norkhairunnisa, M., Yusoff, H. M., & Suraya, M. T. (2015). Investigating the effect of isothermal aging on the morphology and shear strength of Sn-5Sb solder reinforced with carbon nanotubes. *Journal of Alloys and Compounds*, 649, 368–374.
- El-Daly, A. A., & Hammad, A. E. (2010). Elastic properties and thermal behavior of Sn-Zn based lead-free solder alloys. *Journal of Alloys and Compounds*, 505(2), 793–800.
- Elenius, P., & Levine, L. (2000). Comparing Flip-Chip and Wire-Bond Interconnection Technologies. *Chip Scale Review*, 6(6), 81–87.
- Ervina Efzan, M. N., & Marini Aisyah, A. (2012). A review of solder evolution in electronic application. *International Journal of Engineering*, 1(1), 2305–8269.
- Ervina Efzan, M. N., Nur Faziera, M. N., & Siti Rabiattul Aisha, I. (2016). Soldering & Surface Mount Technology A Review : An Evolution of Lead-Free Solder and its Wettability Properties. *Soldering & Surface Mount Technology*, 28(3), 125–132.
- Fellman, J. (2005). A study of the lead-free hot air solder levelling process. *Circuit World*, 31(2), 3–9.
- Frear, D. R. (2007). Issues related to the implementation of Pb-free electronic solders in consumer electronics. *Lead-Free Electronic Solders: Journal of Materials Science: Materials in Electronics*, 319–330.
- Fu, C., Hung, L., Jiang, D., Chang, C., Wang, Y. P., & Hsiao, C. S. (2008). Evaluation of New Substrate Surface Finish : Electroless Nickel / Electroless Palladium / Immersion Gold (ENEPIG). *Proc. of the 58th Conf. on Electronic Components and Technology*. Lake Buena Vista, Florida: IEEE. pp. 1931–1935.

- Fukuda, Y., Ganesan, S. & Pecht, M. (2006). *Lead-Free Legislation, Exemptions, and Compliance. Lead-Free Electronics*. New Jersey: John Wiley & Sons, Inc.
- Goosey, M. (2005). Soldering considerations for lead-free printed circuit board assembly – an Envirowise Guide. *Circuit World*, 31(3), 40–44.
- Guo, B., Kunwar, A., Ma, H., Liu, J., Li, S., Sun, J., Zou, N. & Ma, H. (2015). Effects of soldering temperature and cooling rate on the as-soldered microstructures of intermetallic compounds in Sn-0.7Cu/Cu joint. *Proc. of the 16th Int. Conf. on Electronic Packaging Technology (ICEPT)*. Central South University, China: IEEE. pp. 249–252.
- Guo, Z., Keong, K. G., & Sha, W. (2003). Crystallisation and phase transformation behaviour of electroless nickel phosphorus platings during continuous heating. *Journal of Alloys and Compounds*, 358(1–2), 112–119.
- Guofeng, X., Fei, Q., Tong, A., & Wei, L. (2011). Diffusion-induced stresses in the intermetallic compound layer of solder joints. *Proc. of the 12th Inter. Conf. on Electronic Packaging Technology and High Density Packaging (ICEPT-HDP)*. Shanghai, China: IEEE. pp. 1–5.
- Ha, S.-S., Park, J., & Jung, S.-B. (2011). Effect of Pd Addition in ENIG Surface Finish on Drop Reliability of Sn-Ag-Cu Solder Joint. *Materials Transactions*, 52(8), 1553–1559.
- Hai, H. T., Ahn, J. G., Kim, D. J., Lee, J. R., Chung, H. S., & Kim, C. O. (2006). Developing process for coating copper particles with silver by electroless plating method. *Surface & Coatings Technology*, 201(6), 3788–3792.
- Harper, C.A. (2005). *Electronic Packaging and Interconnection Handbook*, Fourth Edition. New York: McGraw-Hill.
- Ho, C. E., Lin, Y. W., Yang, S. C., Kao, C. R., & Jiang, D. S. (2006). Effects of limited cu supply on soldering reactions between SnAgCu and Ni. *Journal of Electronic Materials*, 35(5), 1017–1024.
- Ho, C. E., Yang, S. C., & Kao, C. R. (2007). Interfacial reaction issues for lead-free electronic solders. *Journal of Materials Science: Materials in Electronics*, 18(1-

3), 155–174.

- Hsiao, C. S. (2007). Investigation of IMC growth and solder joint reliability on new surface finish-ENEPIG. *2007 International Microsystems, Packaging, Assembly and Circuits Technology*, (123), 331–334.
- Hu, J., Hu, A., Li, M., & Mao, D. (2010). Depressing effect of 0.1 wt.% Cr addition into Sn-9Zn solder alloy on the intermetallic growth with Cu substrate during isothermal aging. *Materials Characterization*, 61(3), 355–361.
- Hu, X., Xu, T., Jiang, X., Li, Y., Liu, Y., & Min, Z. (2016). Effects of post-reflow cooling rate and thermal aging on growth behavior of interfacial intermetallic compound between SAC305 solder and Cu substrate. *Applied Physics A: Materials Science and Processing*, 122(4), 1–10.
- Hua, X., Li, Y., & Min, Z. (2014). Interfacial reaction and IMC growth between Bi-containing Sn0.7Cu solders and Cu substrate during soldering and aging. *Journal of Alloys and Compounds*, 582, 341–347.
- Huang, T. S., Tseng, H. W., Lu, C. T., Hsiao, Y. H., Chuang, Y. C., & Liu, C. Y. (2010). Growth Mechanism of a Ternary (Cu,Ni)₆Sn₅ Compound at the Sn(Cu)/Ni(P) Interface. *Journal of Electronic Materials*, 39(11), 2382–2386.
- Huang, X., Lee, S.W. R., Yan, C. C., & Hui, S. (2001). Characterization and analysis on the solder ball shear testing conditions. *Proc. of the 51st Conf. on Electronic Components and Technology*. Orlando, Florida: IEEE. pp. 12–15.
- Illes, B., & Horvath, B. (2013). Whiskering behaviour of immersion tin surface coating. *Microelectronics Reliability*, 53, 755–760.
- Johal, K., Roberts, H., Lamprecht, S., & Wunderlinch, C. (2005). Electroless Nickel / Immersion Gold Process Technology for Improved Ductility of Flex and Rigid-Flex Applications. *Americas*, 25(30), 1–7.
- Kao, B., & Roberts, H. (2010). Pure Palladium in ENEPIG Surface Finishes – Physical properties of the Pd deposition and their influence on soldering and wire bonding. *Proc. of the Conf. on Microsystems, Packaging, Assembly and Circuits Technology (IMPACT)*. Nangang, China: IEEE. pp. 1–4.

- Kar, A., Ghosh, M., Ray, A. K., & Ghosh, R. N. (2007). Effect of copper addition on the microstructure and mechanical properties of lead free solder alloy. *Materials Science and Engineering A*, 459(1–2), 69–74.
- Keller, J., Baither, D., Wilke, U., & Schmitz, G. (2011). Mechanical properties of Pb-free SnAg solder joints. *Acta Materialia*, 59(7), 2731–2741.
- Keong, K. G., Sha, W., & Malinov, S. (2003). Computer modelling of the non-isothermal crystallization kinetics of electroless nickel-phosphorus deposits. *Journal of Non-Crystalline Solids*, 324(3), 230–241.
- Kiat Choon, T. (2003). The effect of the hot air levelling process on skip solder defects in the wave soldering process. *Soldering & Surface Mount Technology*, 15(2), 28–34.
- Kim, J. W., & Jung, S. B. (2004). Experimental and finite element analysis of the shear speed effects on the Sn-Ag and Sn-Ag-Cu BGA solder joints. *Materials Science and Engineering A*, 371(1–2), 267–276.
- Kim, J. W., & Jung, S. B. (2006). Reexamination of the solder ball shear test for evaluation of the mechanical joint strength. *International Journal of Solids and Structures*, 43(7–8), 1928–1945.
- Kim, K. S., Huh, S. H., & Sukanuma, K. (2003). Effects of intermetallic compounds on properties of Sn-Ag-Cu lead-free soldered joints. *Journal of Alloys and Compounds*, 352(1–2), 226–236.
- Kivilahti, J. K. (2002). The Chemical Modeling of Electronic Materials and Interconnections. *Jom*, 54(12), 52–57.
- Kotadia, H. R., Howes, P. D., & Mannan, S. H. (2014). A review: On the development of low melting temperature Pb-free solders. *Microelectronics Reliability*, 54(6–7), 1253–1273.
- Lau, J. H. (1994). *Chip on Board. Technology for Multichip Modules*. New York: Springer Science & Business Media.
- Lau, R., Wong, C.P., Prince, J.L., & Nakayama, W. (1998). *Electronic Packaging Design, Materials, Process, and Reliability*. New York: McGraw-Hill

- Laurila, T., & Vuorinen, V. (2009). Combined thermodynamic-kinetic analysis of the interfacial reactions between Ni metallization and various lead-free solders. *Materials*, 2(4), 1796–1834.
- Laurila, T., Vuorinen, V., & Kivilahti, J. K. (2005). Interfacial reactions between lead-free solders and common base materials. *Materials Science and Engineering R: Reports*, 49(1–2), 1–60.
- Lee, D. J., & Lee, H. S. (2006). Major factors to the solder joint strength of ENIG layer in FC BGA package. *Microelectronics Reliability*, 46(7), 1119–1127.
- Lee, H. T., Chen, M. H., Jao, H. M., & Liao, T. L. (2003). Influence of interfacial intermetallic compound on fracture behavior of solder joints. *Materials Science and Engineering: A*, 358(1–2), 134–141.
- Lee, K. Y., Li, M., Olsen, D. R., Chen, W. T., Tan, B. T. C., & Mhaisalkar, S. (2001). Microstructure, joint strength and failure mechanism of Sn-Ag, Sn-Ag-Cu versus Sn-Pb-Ag solders in BGA packages. *IEEE Transactions on Electronics Packaging Manufacturing*, 25(3), 185–192.
- Lee, L. M., & Mohamad, A. A. (2013). Interfacial reaction of Sn-Ag-Cu lead-free solder alloy on Cu: A review. *Advances in Materials Science and Engineering*, 2013, 1–11.
- Lee, L. M., Nazeri, M. F. M., Haliman, H., & Mohamad, A. A. (2014). Corrosion of Sn-3.0Ag-0.5Cu thin films on Cu substrates in alkaline solution. *Soldering & Surface Mount Technology*, 26(2), 79–86.
- Lee, N. (2006). Optimizing the reflow profile via defect mechanism analysis. *Soldering & Surface Mount Technology*, 11(1), 13–20.
- Lee, Y. H., & Lee, H. T. (2007). Shear strength and interfacial microstructure of Sn-Ag-xNi/Cu single shear lap solder joints. *Materials Science and Engineering A*, 444(1–2), 75–83.
- Li, G. Y., & Chen, B. L. (2003). Formation and Growth Kinetics of Interfacial Intermetallics in Pb-Free Solder Joint. *IEEE Transactions on Components and Packaging Technologies*, 26(3), 651–658.

- Li, M., Xu, H., Kim, J., & Kim, H. (2007). Failure modes of lead free solder bumps formed by induction spontaneous heating reflow. *Journal of Materials Science & Technology*, 23(1), 61–67.
- Li, W. (2015). Failure Analysis on Bad Wetting of ENIG Surface Finish Pads. *Proc. of the 16th Int. Conf. on Electronic Packaging Technology (ICEPT)*. Changsa, China: IEEE. pp. 538–541.
- Li, Y., & Corporation, E. (1997). An experimental study on organic solderability preservative. *Proc. of the 21th Int. Conf. on Electronics Manufacturing Technology (IEMT) Symposium*. Austin, USA: IEEE. pp. 56–61.
- Li Fang, J., & Chan, D. K. (2007). The advantages of mildly alkaline immersion silver as a final finish for solderability. *Circuit World*, 33(2), 43–51.
- Lim, H. P., Ourdjini, A., Bakar, T. A. A., & Tesfamichael, T. (2015). The Effects of Humidity on Tin Whisker Growth by Immersion Tin Plating and Tin Solder Dipping Surface Finishes. *Procedia Manufacturing: Proc. of the 2nd Int. Conf. on Materials, Industrial, and Manufacturing Engineering (MIME)*. Bali, Indonesia: Elsevier. pp. 275–279.
- Lin, K.L., & Shih, C.L. (2003). Wetting interaction between Sn-Zn-Ag solders and Cu. *Journal of Electronic Materials*, 32(2), 95–100.
- Lin, K., & Hsu, K. (2000). Manufacturing and Materials Properties of Ti/Cu/Electroless Ni/Solder Bump on Si. *IEEE Transactions on Components, Packaging, and Manufacturing Technology*, 23(4), 657–660.
- Lin, Y. C., Shih, T. Y., Tien, S. K., & Duh, J. G. (2007). Morphological and microstructural evolution of phosphorous-rich layer in SnAgCu/Ni-P UBM solder joint. *Journal of Electronic Materials*, 36(11), 1469–1475.
- Liu, P., Yao, P., & Liu, J. (2009). Effects of multiple reflows on interfacial reaction and shear strength of SnAgCu and SnPb solder joints with different PCB surface finishes. *Journal of Alloys and Compounds*, 470(1–2), 188–194.
- Liu, X., Huang, M., Zhao, Y., Wu, C. M. L., & Wang, L. (2010). The adsorption of Ag₃Sn nano-particles on Cu-Sn intermetallic compounds of Sn-3Ag-0.5Cu/Cu

- during soldering. *Journal of Alloys and Compounds*, 492(1–2), 433–438.
- Liukkonen, M., Havia, E., Leinonen, H., & Hiltunen, Y. (2009). Application of self-organizing maps in analysis of wave soldering process. *Expert Systems with Applications*, 36(3), 4604–4609.
- Long, E., & Toscano, L. (2013). Electroless Nickel/Immersion Silver- A New Surface Finish PCB Applications. *Metal Finishing*, 111(1), 12–19.
- Loomans, M. E., & Fine, M. E. (2000). Tin-silver-copper eutectic temperature and composition. *Metallurgical and Materials Transactions A*, 31(4), 1155–1162.
- Ma, H., & Suhling, J. C. (2009). A review of mechanical properties of lead-free solders for electronic packaging. *Journal of Materials Science*, 44(5), 1141–1158.
- Ma, H. T., Wang, J., Qu, L., Zhao, N., & Kunwar, A. (2013). A study on the physical properties and interfacial reactions with Cu substrate of rapidly solidified Sn-3.5Ag lead-free solder. *Journal of Electronic Materials*, 42(8), 2686–2695.
- Małeck, A., & Micek-Ilnicka, A. (2000). Electroless nickel plating from acid bath. *Surface and Coatings Technology*, 123(1), 72–77.
- Mallory, G. O. (2009). The Electroless Nickel Plating Bath: Effect of Variables on the Process. in Mallory, G. O., & Hajdu, J. B (1990). *Electroless Plating, Fundamentals & Applications*, 69; 71; 72. Reprint Edition. United State of America: William Adrew. 57-99.
- Manish, R. (2013). *Surface Engineering for Enhanced Performance against wear*. Heidelberg, germany: Springer. pp.79-110.
- Marshall, J. H. (1983). The Nickel Metal Catalyzed Decomposition of Aqueous Hypophosphite Solutions. *Electrochemical Society*, 130(2), 369–372.
- Martyak, N. M. (1994). Characterization of Thin Electroless Nickel Coatings. *Chemistry of Materials*, 6(11), 1667–1674.
- Mayappan, R., Yahya, I., Ghani, N. A. A., & Hamid, H. A. (2014). The effect of adding Zn into the Sn-Ag-Cu solder on the intermetallic growth rate. *Journal of Materials Science: Materials in Electronics*, 25(7), 2913–2922.
- Mhd Noor, E. E., Mhd Nasir, N. F., & Idris, S. R. A. (2016). A review: lead free solder

and its wettability properties. *Soldering & Surface Mount Technology*, 28(3), 125–132.

Mieczkowski, D. (2009). Reflow Soldering Guidelines for Surface-Mount Hybrid Microelectronic Devices and Lumped Element Filter Assemblies Introduction Reflow Process Overview Selection of Solder Paste Selection of Solder Stencil Development of Solder Reflow Profile Initial Pre-H. *API Technologies Philadelphia Operation*, 1–4.

Milad, B. G., & Orduz, M. (2007). Surface Finishes in a Lead-Free World. *Metal Finishing*, 105(1), 25–28.

Milad, G. (2008). Surface finishes in a lead-free world. *Circuit World*, 34(4), 4–7.

Milad, G., & Milad, G. (2013). Is “black pad” still an issue for ENIG? *Circuit World*, 36(1), 10–23.

Mookam, N., & Kanlayasiri, K. (2011). Effect of soldering condition on formation of intermetallic phases developed between Sn–0.3Ag–0.7Cu low-silver lead-free solder and Cu substrate. *Journal of Alloys and Compounds*, 509(21), 6276–6279.

Moon, K.-W., & Boettinger, W. J. (2004). Accurately determining eutectic compositions: The Si-Ag-Cu ternary eutectic. *Jom*, 56(4), 22–27.

Mukherjee, M., & Chakravorti, S. (2014). Assessment of Moisture Diffusion Distance in Pressboard Insulation Within Transformer using Fick's Law. *Proc. of the 18th Conf. on National Power System (NPSC)*. Institute of Technology Guwahati, India: IEEE. pp. 4–7.

Nah, J. W., Gaynes, M. A., Feger, C., Katsurayama, S., & Suzuki, H. (2011). Development of wafer level underfill materials and assembly processes for fine pitch Pb-free solder flip chip packaging. *Proc. of the 61st Conf. on Electronic Components and Technology (ECTC)*. Florida, USA: IEEE. pp. 1015–1022.

Nai, S. M. L., Wei, J., & Gupta, M. (2009). Interfacial intermetallic growth and shear strength of lead-free composite solder joints. *Journal of Alloys and Compounds*, 473(1–2), 100–106.

Neugebauer C.A. (1990). *Electronic Packaging and Interconnection Technology*:

- State of the art and future developments. *IEEE Circuits and Systems*, 3, 2081–2084.
- Noor, E. E. M., Sharif, N. M., Yew, C. K., Ariga, T., Ismail, A. B., & Hussain, Z. (2010). Wettability and strength of In-Bi-Sn lead-free solder alloy on copper substrate. *Journal of Alloys and Compounds*, 507(1), 290–296.
- Ourdjini, A., Azmah Hanim, M. A., Siti Rabiattull Aisha, I., & Chin, Y. T. (2008). Effect of surface finish metallurgy on intermetallic compounds during soldering with tin-silver-copper solders. *Proc. of the 33rd Int. Conf. Electronics Manufacturing Technology (IEMT) Symposium*. Penang: IEEE. pp. 2–5.
- Ourdjini, A., Hanim, M. A. A., Koh, S. F. J., Aisha, I. S., Tan, K. S., & Chin, Y. T. (2006). Effect of Solder Volume on Interfacial Reaction between Eutectic Sn-Pb and Sn-Ag-Cu Solders and Ni(P)-Au Surface Finish. *International Electronic Manufacturing Technology*, 437–442.
- Park, Y. S., Kwon, Y. M., Moon, J. T., Lee, Y. W., Lee, J. H., & Paik, K. W. (2010). Effects of fine size lead-free solder ball on the interfacial reactions and joint reliability. *Proc. of the 60th Conf. on Electronic Components and Technology (ECTC)* Nevada, USA: IEEE. 1436–1441.
- Parquet, Dan T., & Boggs, D. W. (1995). Alternatives To HASL : Users Guide For Surface Finishes By. *Electronic Packaging and Production*, 35(9), 38–42.
- Pascariu, G., Cronin, P., & Crowley, D. (2003). Next-generation electronics packaging using flip chip technology. *Advanced Packaging*, 12(11), 21–22.
- Paw, W., Nable, J., & Swanson, J. (2008). “Behind the Scenes” of Effective OSP Protection in Pb-free Processing. *Proc. of the 3rd Int. Conf. Microsystems, Packaging, Assembly & Circuits Technolog (IMPACT)*. Taiwan, China: IEEE. pp. 411–413.
- Pecht, M. (1991). *Handbook of electronic package design* (vol.76).CRC Press.
- Phil Zarrow and Debra Kopp. (1996). Organic Solderability Preservatives. *Circuits Assembly*, 32 – 35.
- Pun, K., Islam, M. N., & Ng, T. W. (2014). ENEG and ENEPIG Surface Finish for

- Long Term Solderability. *Proc. of the 15th Int. Conf. on Electronic Packaging Technology (ICEPT)*. Chengdu, China: IEEE. pp. 1–5.
- Ramesham, R. (2007). Reliability Assessment of Advanced Flip-Chip Interconnect Electronic Package Assemblies Under Extreme Cold Temperatures Down to -190 °C and -120 °C. *Journal of Microelectronics and Electronic Packaging*, 4(4), 155–166.
- Ramos, G., Gmbh, A. D., & Metzger, D. (2010). Benefits of Pure Palladium for ENEP and ENEPIG Surface Finishes. *Proc. of the 3rd Conf. on Electronic System-Integration Technology (ESTC)*. Berlin, Germany: IEEE. pp. 1–6.
- Rasmussen, F. E., Heschel, M., & Hansen, O. (2003). Batch Fabrication of Through-Wafer Vias In CMOS Wafers for 3-D Packaging Applications. *Proc. of the 53rd Conf. on Electronic Components and Technology*. Louisiana, USA: IEEE. 634–639.
- Reid, M., Pomeroy, M. J., & Robinson, J. S. (2004). Microstructural instability in coated single crystal superalloys. *Journal of Materials Processing Technology*, 153–154, 660–665.
- Reid, M., Punch, J., Collins, M., & Ryan, C. (2008). Effect of Ag content on the microstructure of Sn-Ag-Cu based solder alloys. *Soldering & Surface Mount Technology*, 20(4), 3–8.
- Salam, B., Ekere, N. N., & Rajkumar, D. (2001). Study of the Interface Microstructure of Sn-Ag-Cu Lead-Free Solders and the Effect of Solder Volume on Intermetallic Layer Formation. *Proc. of the 51st Conf. on Electronic Components and Technology*. Florida, USA: IEEE. pp. 471–477.
- Salam, B., Virseda, C., Da, H., Ekere, N.N. & Durairaj (2004). Reflow profile study of the Sn-Ag-Cu solder. *Soldering & Surface Mount Technology* 16(1), 27-34.
- Saliza Azlina, O., Ourdjini, A., Amrin, A., & Siti Rabiattul Aisha, I. (2013). Effect of Solder Volume on Interfacial Reaction between SAC405 Solders and EN(B)EPIG Surface Finish. *Advanced Materials Research*, 845, 76–80.
- Saliza Azlina, O., Ourdjini, A., & Ibrahim, M. H. I. (2015). Comparison between

- SAC405 Lead-Free Solders and EN(P)EPiG and EN(B)EPiG Surface Finishes. *Applied Mechanics and Materials*, 773–774, 232–236.
- Saliza Azlina, O., Ourdjini, A., Siti Rabiatal Aisha, I., & Azmah Hanim, M. A. (2011). Effect of Different Aging Temperatures on Interfacial Reaction between SAC305 and ENEPiG Surface Finish. *Advanced Materials Research*, 415–417, 1181–1185.
- Sapkal, S., Bhagwat, A., Bendrikar-shinde, D., Vadhwan, Z., Gondil, R., & Waikar, R. (2015). Parametric Analysis of Electroless Nickel Plating - A Review. *Proc. of the National Conf. on Modeling, Optimization and control (NCMOC)*. Maharashtra, India: IEEE. pp. 1-5.
- Schlesinger, M. (2010). Electroless and Electrodeposition of Silver. in Schlesinger, M. & Paunovic, M. (2010). *Modern Electroplating*: Fifth Edition. Canada: John Wiley & Sons. Inc. pp. 131-138.
- Schueller, R. (2005). Considerations for Selecting a Printed Circuit Board Surface Finish. *DFR Solution*. Mineapolis, USA. pp. 1–8.
- Sharif, A., Chan, Y. C., Islam, M. N., & Rizvi, M. J. (2005). Dissolution of electroless Ni metallization by lead-free solder alloys. *Journal of Alloys and Compounds*, 388(1), 75–82.
- Sharif, A., Chan, Y. C., & Islam, R. A. (2004). Effect of volume in interfacial reaction between eutectic Sn-Pb solder and Cu metallization in microelectronic packaging. *Materials Science and Engineering B: Solid-State Materials for Advanced Technology*, 106(2), 120–125.
- Shnawah, D. A., Sabri, M. F. M., & Badruddin, I. A. (2012). A review on thermal cycling and drop impact reliability of SAC solder joint in portable electronic products. *Microelectronics Reliability*, 52(1), 90–99.
- Siewert, T., Liu, S., Smith, D. R., & Madeni, J. C. (2002). Database for Solder Properties with Emphasis on New Lead-Free Solders. *NIST & Colorado School of Mines. Release*, 4. pp. 1–77.
- Siti Rabiatal Aisha, I., Ourdjini, A., Azmah Hanim, M. A., & Saliza Azlina, O.

- (2015a). Development of Diffusion Barrier Layer On Copper-Printed Circuit Board Using Electroless Nickle Plating Method. *International Journal of Computational Methods and Experimental Measurements*, 3(4), 329–339.
- Siti Rabiatul Aisha, I., Ourdjini, A., Azmah Hanim, M. A., & Saliza Azlina, O. (2015b). Effect of reflow soldering profile on intermetallic compound formation. *International Journal of Computer Applications in Technology*, 52(4), 244.
- Siti Rabiatul Aisha, I., Ourdjini, A., & Saliza Azlina, O. (2016). The Effectiveness of Bismuth Addition to Retard the Intermetallic Compound Formation. *International Journal of Chemical, Molecular, Nuclear, Material and Metallurgical Engineering*, 10(1), 107–111.
- Slocum, D. (2006). Surface Finishes Utilized in The PC Industry. *MULTEK*. pp. 1–26.
- So, A. C. K., & Chan, Y. C. (1996). Reliability studies of surface mount solder joints - effect of Cu-Sn intermetallic compounds. *IEEE Transactions on Components, Packaging, and Manufacturing Technology: Part B*, 19(3), 661–668.
- Song, F., Lee, S. W. R., Newman, K., Sykes, B., & Clark, S. (2007). Brittle Failure Mechanism of SnAgCu and SnPb Solder Balls during High Speed Ball Shear and Cold Ball Pull Test. *Proc. of the 57th Conf. on Electronic Components and Technology (ECTC)*. Reno, Nevada: IEEE. 364–372.
- Sudagar, J., Lian, J., & Sha, W. (2013). Electroless Nickel, Alloy, Composite and Nano Coatings-A Critical Review. *Journal of Alloys and Compounds*, 571, 183–204.
- Sun, P., Andersson, C., Wei, X., Cheng, Z., Shangguan, D., & Liu, J. (2006). High temperature aging study of intermetallic compound formation of Sn–3.5Ag and Sn–4.0Ag–0.5Cu solders on electroless Ni(P) metallization. *Journal of Alloys and Compounds*, 425(1–2), 191–199.
- Sweatman, K. (2009). Hot Air Solder Leveling in the Lead-free Era. *Global SMT & Packaging*. Las Vegas, Nevada. pp. 10–18.
- Szendiuch, I. (2011). Development in electronic Packaging - Moving to 3D system configuration. *Radioengineering*, 20(1), 214–220.
- Tanaka, H., Tanimoto, M., Matsuda, A., Takeouno, Kurihara, M., & Shiga, S. (1999).

- Pb-Free Surface-Finishing on Electronic Components ' Terminals for Pb-Free Soldering Assembly. *Electronic Materials*, 28(11), 1216–1223.
- Tian, Y., Hang, C., Wang, C., Yang, S., & Lin, P. (2011). Effects of bump size on deformation and fracture behavior of Sn3.0Ag0.5Cu/Cu solder joints during shear testing. *Materials Science and Engineering: A*, 529, 468–478.
- Tong, K. H., Ku, M. T., Hsu, K. L., Tang, Q., Chan, C. Y., & Yee, K. W. (2006). The Evolution of Organic Solderability Preservative (OSP) Process in PCB Application. *Proc. of the Int. Conf. on Microsystems, Packaging, Assembly & Circuits Technology (IMPACT)*. Taipei, China: IEEE. pp. 43–46.
- Tongxiang, L., Wenli, G., Yinghui, Y., & Chunhe, T. (2008). Electroless plating of silver on graphite powders and the study of its conductive adhesive. *International Journal of Adhesion and Adhesives*, 28(1–2), 55–58.
- Tsai, T. N. (2012). Thermal parameters optimization of a reflow soldering profile in printed circuit board assembly: A comparative study. *Applied Soft Computing Journal*, 12(8), 2601–2613.
- Tsao, L. C. (2011). Evolution of nano-Ag₃Sn particle formation on Cu-Sn intermetallic compounds of Sn3.5Ag0.5Cu composite solder/Cu during soldering. *Journal of Alloys and Compounds*, 509(5), 2326–2333.
- Tseng, C. F., Jill Lee, C., & Duh, J. G. (2013). Roles of Cu in Pb-free solders jointed with electroless Ni(P) plating. *Materials Science and Engineering A*, 574, 60–67.
- Tsukamoto, H., Nishimura, T., Suenaga, S., & Nogita, K. (2010). Shear and tensile impact strength of lead-free solder ball grid arrays placed on Ni (P)/Au surface-finished substrates. *Materials Science and Engineering: B*, 171(1–3), 162–171.
- Tummala R. R. (2001). *Fundamental of Microsystems Packaging*. New York: McGraw-Hill.
- Tummala, R., Wong, C. P., & Drive, F. (1997). Materials in Next Generation of Packaging Georgia Institute of Technology. *Advanced Packaging*, 1–3.
- Tu, X. X., Yi, D., Wu, J. & Wang, B. (2017). Influence of Ce addition on Sn-3.0Ag-0.5Cu solder joints: Thermal behaviour, microstructure and mechanical

- properties. *Journal of Alloys and Compounds*. 698(2017), 317-328
- Vianco, P. T. (2008). Performance an overview of surface finishes and their role in printed circuit board solderability and solder joint performance. *Circuit World*, 25(1), 6–24.
- Vianco, P. T. (2015). Hand soldering basics. *Welding Journal*. 47-53.
- Wang, S. J., Kao, H. J., & Liu, C. Y. (2004). Correlation between interfacial reactions and mechanical strengths of Sn(Cu)/Ni(P) solder bumps. *Journal of Electronic Materials*, 33(10), 1130.
- Wang, S. J., & Liu, C. Y. (2003). Study of interaction between Cu-Sn and Ni-Sn interfacial reactions by Ni-Sn3.5Ag-Cu sandwich structure. *Journal of Electronic Materials*, 32(11), 1303–1309.
- Wang, W., Choubey, A., Azarian, M. H., & Pecht, M. (2009). An assessment of immersion silver surface finish for lead-free electronics. *Journal of Electronic Materials*. 38, 815–827.
- Wang, X. J., Zeng, Q. L., Zhu, Q. S., Wang, Z. G., & Shang, J. K. (2010). Effects of Current Stressing on Shear Properties of Sn-3.8Ag-0.7Cu Solder Joints. *Journal of Materials Science & Technology*, 26(8), 737–742.
- Wei, T. C., & Daud, A. R. (2002). The effects of aged Cu-Al intermetallics to electrical resistance in microelectronics packaging. *Microelectronics International*, 19(2), 38–43.
- Wiese, S., Schubert, A., Walter, H., Dudek, R., & Feustel, F. (2001). Constitutive Behaviour of Lead-free Solders vs . Lead-containing Solders - Experiments on Bulk Specimens and Flip-Chip Joints. *Proc. of the 51st Conf. on Electronic Components Technology*. Florida, USA: IEEE. pp. 890–902.
- Wong, C. P., & McBride, R. (1994). Preencapsulation cleaning methods and control for microelectronics packaging. *IEEE Transactions on Components, Packaging, and Manufacturing Technology: Part A*, 17(4), 542–552.
- Wright, A. (2015). Printed Circuit Board Surface Finishes-Advantages and Disadvantages. *Epec Engineered Tecnologies*. Duchaine BLDVD, New Bedford.

1–15.

- Wu, A. T., Chen, M. H., & Huang, C. H. (2009). Formation of intermetallic compounds in SnAgBiIn solder systems on Cu substrates. *Journal of Alloys and Compounds*, 476(1–2), 436–440.
- Wu, C. M. L., Yu, D. Q., Law, C. M. T., & Wang, L. (2004). Properties of lead-free solder alloys with rare earth element additions. *Materials Science and Engineering R: Reports*, 44(1), 1–44.
- Xu, S., Habib, A. H., Pickel, A. D., & McHenry, M. E. (2015). Magnetic nanoparticle-based solder composites for electronic packaging applications. *Progress in Materials Science*, 67, 95–160.
- Yang, J., Huang, J. C., Huang, M., Ku, J. L., Hsieh, A., & Li, K. C. (2010). Failure analysis of ENIG surface finish pad. *Proc. of the 5th Int. Conf. on Microsystems Packaging Assembly and Circuits Technology*. Taipei Hangang, China: IEEE. pp 1–4.
- Yang, M., Li, M., Wang, L., Fu, Y., Kim, J., & Weng, L. (2011). Cu 6Sn 5 morphology transition and its effect on mechanical properties of eutectic Sn-Ag solder joints. *Journal of Electronic Materials*, 40(2), 176–188.
- Yang, S. C., Chang, C. C., Tsai, M. H., & Kao, C. R. (2010). Effect of Cu concentration, solder volume, and temperature on the reaction between SnAgCu solders and Ni. *Journal of Alloys and Compounds*, 499(2), 149–153.
- Yanhong, T., Shihua, Y., Chunqing, W., Xuelin, W., & Pengrong, L. (2010). Volume Effect of Shear Fracture Behavior of Sn3. 0Ag0. 5Cu/Cu Lead-free Solder Joints. *Acta Metall Sin*, 46(3), 366–371.
- Yeh, C. L., & Lai, Y. S. (2006). Transient fracturing of solder joints subjected to displacement-controlled impact loads. *Microelectronics Reliability*, 46(5–6), 885–895.
- Yin, L., Li, W., Wei, S., & Xu, Z. (2011). Size and Volume Effects in Microscale Solder Joint of Electronic Packaging. *Proc. of the 12nd Int. Conf. on Electronic Packaging Technology and High Density Packaging (ICEPT-HDP)*. Shanghai,

China: IEEE. pp. 832–834.

Yoon, J., & Jung, S. (2005). Interfacial reactions between Sn – 0.4Cu solder and Cu substrate with or without ENIG plating layer during reflow reaction. *Alloys and Compounds*, 396, 122–127.

Yoon, J. W., & Jung, S. B. (2008). Effect of immersion Ag surface finish on interfacial reaction and mechanical reliability of Sn-3.5Ag-0.7Cu solder joint. *Journal of Alloys and Compounds*, 458(1–2), 200–207.

Yoon, J. W., Kim, S. W., & Jung, S. B. (2005a). IMC morphology, interfacial reaction and joint reliability of Pb-free Sn-Ag-Cu solder on electrolytic Ni BGA substrate. *Journal of Alloys and Compounds*, 392(1–2), 247–252.

Yoon, J. W., Kim, S. W., & Jung, S. B. (2005b). Interfacial reaction and mechanical properties of eutectic Sn-0.7Cu/Ni BGA solder joints during isothermal long-term aging. *Journal of Alloys and Compounds*, 391(1–2), 82–89.

Yoon, J. W., Noh, B. I., & Jung, S. B. (2011). Comparative study of ENIG and ENEPIG as surface finishes for a Sn-Ag-Cu solder joint. *Journal of Electronic Materials*, 40(9), 1950–1955.

Yoon, J. W., Noh, B. I., Kim, B. K., Shur, C. C., & Jung, S. B. (2009). Wettability and interfacial reactions of Sn-Ag-Cu/Cu and Sn-Ag-Ni/Cu solder joints. *Journal of Alloys and Compounds*, 486(1–2), 142–147.

Yu, D. Q., & Wang, L. (2008). The growth and roughness evolution of intermetallic compounds of Sn-Ag-Cu/Cu interface during soldering reaction. *Journal of Alloys and Compounds*, 458(1–2), 542–547.

Yu, D. Q., Wu, C. M. L., Law, C. M. T., Wang, L., & Lai, J. K. L. (2005). Intermetallic compounds growth between Sn-3.5Ag lead-free solder and Cu substrate by dipping method. *Journal of Alloys and Compounds*, 392(1–2), 192–199.

Zeng, G., Xue, S., Zhang, L., Gao, L., Dai, W., & Luo, J. (2010). A review on the interfacial intermetallic compounds between Sn-Ag-Cu based solders and substrates. *Journal of Materials Science: Materials in Electronics*, 21(5), 421–440.

- Zeng, K., & Tu, K. N. (2002). Six cases of reliability study of Pb-free solder joints in electronic packaging technology. *Materials Science and Engineering*, 38, 55–105.
- Zeng, K., Vuorinen, V., & Kivilahti, J. K. (2002). Interfacial Reactions Between Lead-Free SnAgCu Solder and Ni(P) Surface Finish on Printed Circuit Boards. *IEEE Transactions on Components and Packaging Manufacturing*, 25(3), 162–167.
- Zhang, L., He, C. W., Guo, Y. H., Han, J. G., Zhang, Y. W., & Wang, X. Y. (2012). Development of SnAg-based lead free solders in electronics packaging. *Microelectronics Reliability*, 52(3), 559–578.
- Zhang, L., Xue, S. B., Zeng, G., Gao, L. L., & Ye, H. (2011). Interface reaction between SnAgCu/SnAgCuCe solders and Cu substrate subjected to thermal cycling and isothermal aging. *Journal of Alloys and Compounds*, 510(1), 38–45.
- Zheng, Y., Hillman, C., McCluskey, P. (2002). Intermetallic Growth on PWBs Soldered with Sn3.8Ag0.7Cu. *Proc. of the 52nd Conf. Electronic Components and Technology*. San Diego, United State: IEEE. 1226–1231.
- Zhou, Y., Yang, P., & Yuan, C. (2013). Electrochemical Migration Failure of the Copper Trace on Printed Circuit Board Driven by Immersion Silver Finish. *Chemical Engineering Transactions*, 33, 559–564.
- Zimprich, P., Saeed, U., Betzwar-Kotas, A., Weiss, B., & Ipser, H. (2007). Mechanical Size Effects in Miniaturized Lead-Free Solder Joints. *Journal of Electronic Materials*, 37(1), 102–109.